Ice Properties of Mixed-Phase Arctic Boundary-Layer Clouds

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## Aerosol Indirect Effects

### Table 1. Overview of the different aerosol indirect effects and range of the radiative budget perturbation at the top-of-the-atmosphere ($F_{TOA}$) [W m$^{-2}$], at the surface ($F_{SFC}$) and the likely sign of the change in global mean surface precipitation ($P$) as estimated from Fig. 2 and from the literature cited in the text.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Cloud type</th>
<th>Description</th>
<th>$F_{TOA}$</th>
<th>$F_{SFC}$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indirect aerosol effect for clouds with fixed water amounts (cloud albedo or Twomey effect)</td>
<td>All clouds</td>
<td>The more numerous smaller cloud particles reflect more solar radiation</td>
<td>$-0.5$ to $-1.9$</td>
<td>Similar to $F_{TOA}$</td>
<td>n/a</td>
</tr>
<tr>
<td>Indirect aerosol effect with varying water amounts (cloud lifetime effect)</td>
<td>All clouds</td>
<td>Smaller cloud particles decrease the precipitation efficiency thereby prolonging cloud lifetime</td>
<td>$-0.3$ to $-1.4$</td>
<td>Similar to $F_{TOA}$</td>
<td>decrease</td>
</tr>
<tr>
<td>Semi-direct effect</td>
<td>All clouds</td>
<td>Absorption of solar radiation by soot may cause evaporation of cloud particles</td>
<td>$+0.1$ to $-0.5$</td>
<td>Larger than $F_{TOA}$</td>
<td>decrease</td>
</tr>
<tr>
<td>Thermodynamic effect</td>
<td>Mixed-phase clouds</td>
<td>Smaller cloud droplets delay the onset of freezing</td>
<td>$?$</td>
<td>$?$</td>
<td>Increase or decrease</td>
</tr>
<tr>
<td>Glaciation indirect effect</td>
<td>Mixed-phase clouds</td>
<td>More ice nuclei increase the precipitation efficiency</td>
<td>$?$</td>
<td>$?$</td>
<td>Increase</td>
</tr>
<tr>
<td>Rimming indirect effect</td>
<td>Mixed-phase clouds</td>
<td>Smaller cloud droplets decrease the riming efficiency</td>
<td>$?$</td>
<td>$?$</td>
<td>Decrease</td>
</tr>
</tbody>
</table>

Source: Lohmann and Feichter, Global indirect aerosol effects: a review, ACP 5:715, 2005
Aerosol Indirect Effects

- ice clouds
  - longwave effects tend to cancel shortwave effects
  - some clouds not aerosol limited [Lohmann and Kärcher, 2002; Fridlind et al., 2004]
  - ice nuclei could play a greater role [Kärcher and Lohmann, 2003]

- caveats
  - emissions can *decrease* aerosol numbers [Singh et al., 2002; Spracklen et al., 2006]
  - indirect effect studies often not constrained by observations
  - observations difficult to screen for aerosol-meteorology covariance
  - meteorology can modulate indirect effects [e.g., Ackerman et al., 2004]
Aerosol Indirect Effects

- cloud longwave forcing implicated in sea ice loss [Francis and Hunter, 2006]
- warm clouds in the Arctic region
  - albedo effect outweighs longwave effect [Intrieri et al., 2002]
    - brighter surfaces
    - wintertime darkness
  - positive anthropogenic $F_{SFC}$ [Garrett and Zhao, 2006; Lubin and Vogelmann, 2006]
    - thin clouds
    - concurrence with springtime pollution
Aerosol Indirect Effects

- mixed-phase clouds in the Arctic region
  - current level of understanding
    - common during transition seasons
    - glaciation desiccates cloud mass
    - ice initiation depends upon ice nuclei ($T > -36^\circ C$)
    - pollution aerosols not rich in ice nuclei
    - much more ice when drop numbers are low [Rangno and Hobbs, 2001]
  - field experiments
    - 2004 Mixed-Phase Arctic Cloud Experiment (M-PACE)
    - 1998 FIRE-Arctic Cloud Experiment (SHEBA)
    - 1984 Beaufort Arctic Storms Experiment (BASE)
  - conclusions
    - ice nucleation is very poorly understood
    - pollution aerosols probably suppress glaciation
    - likely additional enhancement of springtime warming
Mixed-Phase Arctic Cloud Experiment
Model Description

- Dynamics framework
  - large-eddy simulation [Stevens and Bretherton, 1997]
  - dynamic Smagorinsky subgrid model [Kirkpatrick et al., 2006]
  - 3.2 x 3.2 x 2.0 km, doubly periodic, 250-m sponge layer at top
  - 64 x 64 x 96 mesh, 50 m x 20 m uniform grid
  - 2-stream radiative transfer, 44 wavelength bands [Toon et al., 1989]
  - specified SST, advective flux and subsidence profiles, translation
  - similarity sensible and latent heat fluxes (held constant during spin-up)

- Size-resolved microphysics [Jensen et al., 1994; Ackerman et al., 1995]
  - diagnostic aerosols: 20 bins, 10 nm–1 \( \mu \)m diameter
  - liquid: 20 bins, 2 \( \mu \)m–2 mm
  - ice: 20 bins, 2 \( \mu \)m–5 mm
  - prognostic ice nuclei: 10 bins, most to least easily nucleated
  - = 90 variables
Model Results

Liquid Supersaturation (%)

Liquid Water Mixing Ratio (g/kg)

Ice Water Mixing Ratio (g/kg)

Ice Supersaturation (%)

Droplet Distribution

Residual radius (um)

SS = -0.14 %N
drops = 18.4 cm
and

Ice Crystal Distribution

Residual radius (um)

T = -12.8 C

SSi = 13.18 %N

ice = 1.88 L

and

\[ r_{eff} = 169.1 \mu m \]
### Model Description

- **Microphysical processes**
  - drop activation, condensation/evaporation
  - particle sedimentation
  - drop-drop gravitational collection [Hall, 1980; Beard and Ochs, 1984]
  - heterogeneous ice formation, deposition/sublimation
  - phoretic scavenging [Young, 1974], 0.5 $\mu$m diameter ice nuclei [Rogers, 2001]
  - drop-ice gravitational collection [Hall, 1980]
  - ice multiplication

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Temp, C</th>
<th>Supersat</th>
<th>Dependence</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary modes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>contact</td>
<td>$-4 &gt; T &gt; -14$</td>
<td>—</td>
<td>$f_{lin}(T)$</td>
<td>drop + $IN_{aer} \rightarrow$ ice (phoresis)</td>
</tr>
<tr>
<td>condensation</td>
<td>$-8 &gt; T &gt; -22$</td>
<td>$S_w &lt; S$</td>
<td>$f_{lin}(T)$</td>
<td>$IN_{aer} \rightarrow$ ice</td>
</tr>
<tr>
<td>deposition</td>
<td>$-10 &gt; T$</td>
<td>$S_i &lt; S &lt; 0.3$</td>
<td>$f_{exp}(S)$</td>
<td>$IN_{aer} \rightarrow$ ice</td>
</tr>
<tr>
<td>immersion</td>
<td>$-10 &gt; T &gt; -24$</td>
<td>—</td>
<td>$f_{lin}(T)$</td>
<td>drop + $IN_{drop} \rightarrow$ ice</td>
</tr>
<tr>
<td><strong>Multiplication</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rime-splintering</td>
<td>$-3 &gt; T &gt; -8$</td>
<td>—</td>
<td>$f_{lin}(T)$</td>
<td>one crystal per 250 collisions</td>
</tr>
</tbody>
</table>
Model Results vs Observations

(a) Measurements

(b) Model: 0.2/L IN

(c) Model: 0.2/L IN, slow fall velocity

(d) Model: 200/L IN
**Literature Survey**

<table>
<thead>
<tr>
<th>TYPE IV</th>
<th>TYPE V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(b) Moderately Supercooled Stratiform Clouds (Tops −10° to −20°C)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Small droplets at cloud top, possible ice, little or no precipitation</strong></td>
<td><strong>Large droplets at cloud top, ice, precipitation</strong></td>
</tr>
<tr>
<td>- Droplet concentrations &gt; 100 cm(^{-3})</td>
<td>- Droplet concentrations typically &lt; 100 cm(^{-3})</td>
</tr>
<tr>
<td>- Maximum effective droplet radius &lt; 10 μm</td>
<td>- Maximum effective radius &gt; 10 μm</td>
</tr>
<tr>
<td>- Maximum threshold droplet diameter &lt; 20 μm</td>
<td>- Maximum threshold droplet diameter &gt; 20 μm</td>
</tr>
<tr>
<td>- Ice concentrations nil or a few per liter</td>
<td>- Ice concentrations 10-100 per liter</td>
</tr>
</tbody>
</table>

Image source: Rangno and Hobbs, Ice particles in stratiform clouds in the Arctic and possible mechanisms for the production of high ice concentrations, JGR 106:15,065, 2001
## Model Description

- Drop shattering [Brownscombe and Thorndike, 1968; Hobbs and Alkezweeny, 1968]
- Ice fragmentation [Vardiman, 1978]
- Evaporation nuclei [Beard, 1992] and electroscavenging [Tinsley et al., 2000]
- Evaporation freezing [Cotton and Field, 2002]

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<tr>
<td>Multiplication</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rime-splintering</td>
<td>$-3 &gt; T &gt; -8$</td>
<td>—</td>
<td>$f_{lin}(T)$</td>
<td>crystal per 250 collisions</td>
</tr>
<tr>
<td>drop shattering</td>
<td>$0 &gt; T$</td>
<td>—</td>
<td>$D_{drop} &gt; 50 \mu m$</td>
<td>multiplication factor $= 2$</td>
</tr>
<tr>
<td>ice fragmentation</td>
<td>$0 &gt; T$</td>
<td>—</td>
<td>$f_{lin}(\Delta mom^2)$</td>
<td>up to 20–60 fragments</td>
</tr>
<tr>
<td>Other processes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>evaporation nuclei</td>
<td>$0 &gt; T$</td>
<td>$S &lt; S_w$</td>
<td>—</td>
<td>$1/10^4$ drops $\rightarrow$ IN$_{aer}$</td>
</tr>
<tr>
<td>charge enhancement</td>
<td>$0 &gt; T$</td>
<td>—</td>
<td>$f(D_{drop})$</td>
<td>evaporated drop retains charge</td>
</tr>
<tr>
<td>evaporation freezing</td>
<td>$0 &gt; T$</td>
<td>$S &lt; S_w$</td>
<td>—</td>
<td>‘some’ drops ‘just freeze’</td>
</tr>
</tbody>
</table>
Model Results vs Observations

(a) Measurements

(b) Model: Surface source

(c) Model: Evaporation IN

(d) Model: Evaporation freezing
Conclusions from M-PACE

- measured ice nuclei do not explain observed ice
- evaporation nuclei or evaporation freezing could work
- evaporation nuclei from oceanic organic sources? [Leck and Bigg, 2005]
Source: I. V. Gorodetskaya, L.-B. Tremblay, B. Liepert, M. A. Cane, and R. I. Cullather, Modification of the Arctic Ocean short-wave radiation budget due to cloud and sea ice properties in coupled models and observations, J. Clim., submitted
Source: I. V. Gorodetskaya, L.-B. Tremblay, B. Liepert, M. A. Cane, and R. I. Cullather, Modification of the Arctic Ocean short-wave radiation budget due to cloud and sea ice properties in coupled models and observations, J. Clim., submitted